# Lingaya's Vidyapeeth

**SIMULATION AND MODELLING OF DROPLET EVAPORATION TO CHARACTERIZE THE EFFECT OF SURFACE THERMAL CONDUCTIVITY AND DROPLET FLUID PROPERTY**

# SYNOPSIS

**Submitted**

**in the partial fulfillment for the**

**Degree of**

**Doctor of Philosophy**

**by**

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**Under the guidance**

**of**

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**Name of College** : Lingaya's Vidyapeeth

1. **Title:**

   SIMULATION AND MODELLING OF DROPLET EVAPORATION TO CHARACTERIZE THE EFFECT OF SURFACE THERMAL CONDUCTIVITY AND DROPLET FLUID PROPERTY

2. **Introduction**:

   The focus on the evaporation behavior of droplet is more initiated in the recent past due to the various scientific and technological problems associated with the droplet evaporation. Fang & Ward (1999) showed through experiment that there are temperature discontinuities at surface of the droplet which is evaporating and the temperature discontinuities are much larger and are also in opposite direction from the original prediction by the non-equilibrium thermodynamics or Classical kinetic theory which says that the temperature in the liquid just below the free surface of a evaporating droplet is lower than that of the vapor just above the free surface. Previous researchers assumed the vapor saturation concentration just above droplet free surface as a constant, but Sultan et al. (2005) generalized the vapour saturation concentration just above evaporating droplet free surface as a function of temperature rather than a constant. The evaporating film linear stability was investigated by Sultan et al. (2005) and verified the results of Poulard, B´enichou & Cazabat (2003).

   With the growing interest of scientific and important technological problems of liquid droplet evaporation, more study is initiated focusing the behavior of evaporation of a droplet in recent past. The evaporation of a droplet on the basis of constant angle of contact and on the basis of constant area of contact has been studied by Picknett and Bexon (1) in the year 1977 and suggested a theoretical model assuming that the surface just above the droplet contains saturated vapor and the liquid vapour that diffuses from the liquid droplet is the process which is rate –limiting type ((2) and (3)).

   The hot wave formation from centre towards the boundary of a evaporating droplet due to the hot environment was studied by Koffi Sagna et al.(2013) . Suspended droplet evaporation characteristic was studied by Wang et al.(2017).Effect of evaporation by substrate inclination was studied and modelled by Charitatos et

al,(2021).Mathematical analysis of evaporation of a droplet surrounded by an environment of air vapor mixture and based on steady state mass flux , energy balance and equation of momentum was given by Toniniet al.(2022).The evaporation of a binary droplet was studied by Rajuet al. (2022) and suggested that the particles accumulation takes place at a defined radius at the interface of liquid and air. The accumulation at a specific radius makes a ring known as Marangoni Ring. In all the above mentioned discussions the researchers has used different substrates , contact angles , liquids , substrate angles without considering effect of substrate conductivity.

Hu and Larson further suggested the thermocapillary effect known as Maragnoni effect by generalizing the numerical analysis of the flow inside the droplet Hu and Larson. Ristenpart et al. studied recirculation due to thermocapillary action and observed that the relative thermal conductivity of the substrate and the droplet fluid along with the contact angle governs the recirculation within the droplet. All the work described above are theoretical assuming that layer above the free surface of the droplet is saturated with vapor. The evaporation of a droplet in hot environment and the formation of hot wave from center of the evaporating droplet towards the boundary was studied by Koffi Sagna et al. ( 2013).The evaporation character of suspended droplet was measured by WANG et al.. A new mathematical model developed by analyzing mathematically on the basis of energy balance , steady state mass flux and momentum equation for a evaporating droplet surrounded by air and vapor mixture environment was given recently by Tonini et al. Charitatos et al. developed a model to study the effect of the inclination of substrate over the evaporation effect of droplet and concluded that the steeper substrate decreases the rate of evaporation of droplet. Raju et al. suggested that during evaporation of a binary droplet, the accumulation of the particles occurs at a particular radius where there is interface between liquid and air along with the accumulation along the substrate contact line. This accumulation at a particular radius produces a ring known as Marangoni ring. Most of above discussed experiment of evaporation of droplet has used various substrates , liquids , substrate angles , contact angles but without considering the effect of thermal conductivity of different substrates.

3. **Work map:**

We will consider variation of saturation concentration with respect to temperature and humidity experimentally.

We will include saturation concentration variation with temperature and couple with atmospheric humidity to reproduce and justify the experimental outcome with the help of a basic model

4. **Review of literature:**

| SR NO | AUTHER'S NAME | PAPER TITLE | JOURNAL DETAILS | WORK DONE ,FINDINGS AND CONCLUSION |
|---|---|---|---|---|
| 1 | S.Ya. Misyura Institute of Thermophysics Siberian Branch, Russian Academy of Sciences, 1. Akad. Lavrentyev Ave., Novosibirsk 630090, Russia | Nucleate boiling in bidistillate droplets | International Journal of Heat and Mass Transfer 71 **(2014)** 197-205 | Dynamics of Nucleate boiling on rough and polished copper surface was studied and the thermal field of droplet surface was measured by thermal imager. The findings are as follows 1. The ratio of an average distance between the bubbles to their diameter is less than 3, and this indicates the nonlinear interaction of bubbles and system inclination towards the chaotic behavior. Despite this fact, this complex open dissipative and nonlinear system has the obvious tendency to self-organization of the ordered structures. 2. At low superheat the contact line is fixed. At high superheat and high rate of bubble growth, the contact line of droplet moves continuously and the conjugated boundary conditions change (droplet surface, wall temperature). 3. While approaching the detachment point (boiling crisis at Leidenfrost temperature), total vapor concentration in the droplet is essentially lower than that for pool boiling of water. 4. Heat transfer on the polished golden-plated surface is significantly lower than that for the rough copper wall. When calculating the radius of a critical nucleus (for the surface studied in this work), it is necessary to consider not the root-meansquare value for all pores, but the cavities with characteristic geometry and neutral wettability (the |

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| | | | | contact angle is close to 90). |
| SR NO | AUTHOR'S NAME | PAPER TITLE | JOURNAL DETAILS | WORK DONE ,FINDINGS AND CONCLUSION |
| 2 | P. Tartarini, M.A. Corticelli and L. Tarozzi DIMeC, University of Modena and Reggio Emilia, Via Vignolese 905, 41100 Modena, Italy | Dropwise Cooling: Experimental Tests by Infrared Thermography and Numerical Simulations | Applied Thermal Engineering **(2008),** doi: 10.1016/j.applthermaleng. 2008.06.011 | The solid-liquid interface temperature has been monitored from below through a transparent-to-infrared material. That material had been coated with a very thin layer of high-emissivity, opaque paint on its upper side, so that it could effectively respond to the infrared camera located below. The experimental results concerning transient temperature distributions confirmed many typical trends of dropwise cooling, and the direct observation of the solid-liquid interface temperature enhanced the comprehension of the phenomenology of the interactions between droplets and hot surfaces. |
| 3 | Odile Carrier , Noushine Shahidzadeh-Bonn , Rojman Zargar , Mounir Aytouna , Mehdi Habibi , Jens Eggers3 and Daniel Bonn,Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, Science Park 904, 1098XH | Evaporation of water: evaporation rate and collective effects | J. Fluid Mech. **(2016),** vol. 798, pp. 774–786. c Cambridge University Press 2016 doi:10.1017/jfm.2016.356 774 | Here investigation is done on the evaporation of drops over a wide range of length scales, in the limit that the temperature is almost uniform throughout the system – i.e. temperature gradients induced by evaporation are small.<br>The findings are as follows<br>If several drops are present, separated by a distance comparable to their radius, the evaporation from a single drop is reduced significantly, owing to the saturation of the atmosphere by the other drops. Evaporation also becomes non-uniform, with drops near the border vanishing first. The size distribution within a spray of drops is strongly distorted by the interaction. |

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| SR NO | AUTHOR'S NAME | PAPER TITLE | JOURNAL DETAILS | WORK DONE ,FINDINGS AND CONCLUSION |
| 4 | Hua Hu and Ronald G. Larson Department of Chem. Eng., UniVersity of Michigan, Ann Arbor, Michigan 48109-2136 | Evaporation of a Sessile Droplet on a Substrate | J. Phys. Chem. B **(2002),** 106, 1334-1344 | An FEM model is developed to solve the vapor concentration distribution and the evaporation flux above a droplet that is small enough that its shape is not influenced by gravity and is therefore a spherical cap. The results predicted by this model compare very well with literature data without parameter fitting. The FEM results are also confirmed by an analytical formula derived by Lebedev for the electrostatic potential produced by a charged lens and by the theoretical solution of Picknett and Bexon. |
| 5 | Florian Carle, Sergey Semenov, Marc Medale, David Brutin Aix Marseille Universite, IUSTI UMR 7343, 13013 Marseille, France | Contribution of convective transport to evaporation of sessile droplets: Empirical model | International Journal of Thermal Sciences 101 **(2016)** 35-47 | In the present article, the contribution of surrounding air convection on droplet evaporation rates was investigated both experimentally and numerically during the evaporation of an ethanol sessile droplet. Although a significant discrepancy was observed between the experiments and the isothermal diffusiondriven model in usual gravity conditions, a good agreement was observed in the absence of gravity, regardless of the substrate temperature. The experimental and numerical results validate the assumptions inherent in the model under reduced gravity conditions and consequently highlight the fact that the under-prediction of this model is due to the contribution of the buoyant t |

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| | | | | convection in the gas phase, which develops under the action of gravity. |
| SR NO | AUTHOR'S NAME | PAPER TITLE | JOURNAL DETAILS | WORK DONE ,FINDINGS AND CONCLUSION |
| 6 | P.L. Kelly-Ziona,C.J. Pursell b, S. Vaidyaa, J. Batraa a Engineering Science Department, Trinity University, San Antonio, TX 78212, USA b Chemistry Department, Trinity University, San Antonio, TX 78212, USA | Evaporation of sessile drops under combined diffusion and natural convection | Colloids and Surfaces A: Physicochemical and Engineering Aspects 381 **(2011)** 31-36 | For the experimental conditions of this study the quasi-steady, diffusion-controlled evaporation model was shown to be inadequate to predict the evaporation rates. Measured rates were from 50% to 475% greater than the values computed by the diffusion controlled evaporation model. Based on evidence provided by the higher rates are attributed to an increase in the transport of the vapor from the drop surface by natural convection. |
| 7 | A. N. Pavlenko1, E. A. Tairov2, V. E. Zhukov1, A. A. Levin2, and M. I. Moiseev1 1Kutateladze Institute of Thermophysics , Siberian Branch, Russian Academy of Sciences, pr. Akad. Lavrent'eva 1, Novosibirsk, 630090 Russia 2Melentiev Energy Systems Institute, Siberian Branch, | Dynamics of Transient Processes at Liquid Boiling-up in the Conditions of Free Convection and Forced Flow in a Channel under Nonstationary Heat Release Academy of Sciences, Irkutsk, Russia | ISSN 1810-2328, Journal of Engineering Thermophysics, 2014, Vol. 23, No. 3, pp. 173–193. c Pleiades Publishing, Ltd., **2014** | The experimental investigations of the dynamics of propagation of the self-sustained evaporation front have shown that the small-scale disturbances are a result of development of interface instability in the frontal region and in the region of removing away the superheated liquid layer by the growing vapor layer. |

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| SR NO | AUTHOR'S NAME | PAPER TITLE | JOURNAL DETAILS | WORK DONE ,FINDINGS AND CONCLUSION |
| 8 | Erik Dietrich , Sander Wildeman , Claas Willem Visser , Kevin Hofhuis , E. Stefan Kooij , Harold J. W. Zandvliet , Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands. | Role of natural convection in the dissolution of sessile droplets | arXiv:1601.05226v2 [physics.flu-dyn] 24 May **2016** | The value for Rat presented in this work provides an important indication to determine the dominant transport mechanism in droplet dissolution. In conjunction with this, the convective dissolution model allows for more accurate predictions of droplet dissolution times. |
| 9 | Christian Diddens, Huanshu Tan , Pengyu Lv, Michel Versluis , J. G. M. Kuerten , Xuehua Zhang and Detlef Lohse Physics of Fluids group, Department of Science and Technology, Mesa+ Institute, and J. M. Burgers Centre for Fluid Dynamics, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands | Evaporating pure, binary and ternary droplets: thermal effects and axial symmetry breaking | J. Fluid Mech. (2017), vol. 823, pp. 470–497. c Cambridge University Press **2017** doi:10.1017/jfm.2017.312 | The numerical predictions and the experimental data for a pure water droplet and a binary water–ethanol droplet have validated the axisymmetric finite element method model of Diddens |

| SR NO | AUTHOR'S NAME | PAPER TITLE | JOURNAL DETAILS | WORK DONE ,FINDINGS AND CONCLUSION |
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| 10 | By N O U S H I N E S H A H I D Z A D E H - B O N N, University of Amsterdam, Valckenierstraat 65 1018 XE Amsterdam, the Netherlands | Evaporating droplets | J. Fluid Mech. **(2019),** vol. 549, pp. 307–313. c 2006 Cambridge University Press doi:10.1017/S0022112005008190 | The interpretation of a non-zero contact angle for a completely wetting liquid is not straightforward, since the equilibrium contact angle is given by the (equilibrium) surface and interfacial tensions |
| 11 | Torgrim Log Department of Engineering, Stord/Haugesund University College, Bjoernsonsgt. 45, 5528 Haugesund, Norway | Water droplets evaporating on horizontal semi-infinite solids at room temperature | Applied Thermal Engineering 93 **(2016)** 214–222 | In contradiction to the general belief assuming that air cooled by the water droplet is moving downwards, it is shown that the transport of water vapour and entrained air is mainly directed upwards due to the low molar mass of water vapour |
| 12 | V. E. Nakoryakov and N. I. GrigoryevaKutateladze Institute of Thermophysics, Siberian Branch, Russian Academy of Sciences, pr. Akad. Lavrent'eva 1, Novosibirsk, 630090 Russia | Nonisothermal Absorption in Thermotransformers | ISSN 1810-2328, Journal of Engineering Thermophysics, **2018**, Vol. 19, No. 4, pp. 196–271 | Analysis of the data on the surface tension of aqueous lithium bromide solution with different surfactant additives under conditions of operating absorber of the heat pump has shown that their usage for mathematical modeling is unfeasible. |

| SR NO | AUTHOR'S NAME | PAPER TITLE | JOURNAL DETAILS | WORK DONE ,FINDINGS AND CONCLUSION |
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| 13 | Torgrim Log * Department of Engineering, Stord/Haugesund University College, Bjoernsonsgt. 45, 5528 Haugesund, Norway | Water droplets evaporating on horizontal semi-infinite solids at room temperature | Applied Thermal Engineering 93 **(2019)** 214–222 | In contradiction to the general belief assuming that air cooled by the water droplet is moving downwards, it is shown that the transport of water vapour and entrained air is mainly directed upwards due to the low molar mass of water vapour. Mathematical solutions based on finite plane sources and semi-infinite solids give reasonable estimates of droplet temperatures and evaporation rates. Based on this knowledge, principle evaporation dependencies on substrate material and droplet sizes have been established. This is verified for droplets of about 10 mm radius evaporating on XPS-foam, PMMA and stainless steel. It is shown that natural convection takes place in the experiments ensuring evaporation rates significantly higher than pure diffusion into completely stagnant air. |
| 14 | V. E. Nakoryakov* and N. I. Grigoryeva** Kutateladze Institute of Thermophysics, Siberian Branch, Russian Academy of Sciences, pr. Akad. Lavrent'eva 1, Novosibirsk, 630090 Russia | Nonisothermal Absorption in Thermotransformers | ISSN 1810-2328, Journal of Engineering Thermophysics, **2020**, Vol. 19, No. 4, pp. 196–271. c Pleiades Publishing, Ltd., 2010. | The evaporator and the absorber, as the generator and the condenser, have coupled vapor spaces, but with different pressures. The pressure in the evaporator and the absorber is much lower than in the generator and the condenser. An aqueous lithium bromide solution falls down on the outer surface of the tubes, whereas in the condenser and the evaporator, it is water. |

5. **Technical programme:**

(i) Name of the experiment : Temperature Controlled Evaporation Setup.

(ii) Location: Field / Lab : Material Science lab (K110) , Lingaya's Vidyapeeth

(iii) Methodology : Droplet will be developed with dispenser over different Substrate.The ambient conditions inside the setup will be recorded and then time of evaporation and the evaporation process will be recorded by high resolution camera under different base temperatures.

(iv) Observations to be recorded under : Time of evaporation of droplet over different substrates

different base temperatures at same ambient temperature and humidity.

(v)Statistical analysis : The data obtained will be analysed using suitable software .

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